Development of a neutron imaging diagnostic for inertial confinement fusion experiments

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Pinhole imaging of the neutron production in laser-driven inertial confinement fusion experiments can provide important information about the performance of various capsule designs. This requires the development of systems capable of spatial resolutions on the order of 5 μm or less for source strengths of 10^{15} and greater. We have initiated a program which will lead to the achievement of such a system to be employed at the National Ignition Facility (NIF) facility. Calculated neutron output distributions for various capsule designs will be presented to illustrate the information which can be gained from neutron imaging and to demonstrate the requirements for a useful system. We will describe the lines-of-sight available at NIF for neutron imaging and explain how these can be utilized to reach the required parameters for neutron imaging. We will describe initial development work to be carried out at the Omega facility and the path which will lead to systems to be implemented at NIF. Beginning this year, preliminary experiments will be aimed at achieving resolutions of 30–60 μm for direct-drive capsules with neutron outputs of about 10^{14}. The main thrust of these experiments will be to understand issues related to the fabrication and alignment of small diameter pinhole systems as well as the problems associated with signal-to-background ratios at the image plane. Subsequent experiments at Omega will be described. These efforts will be aimed at achieving resolutions of about 10 μm. Proposed developments for new imaging systems as well as further refinement of pinhole techniques will be presented. [DOI: 10.1063/1.1329883]

I. INTRODUCTION

Neutron imaging has proven possible on laser driven implosions, first on the Nova laser,[1] then on Gekko XII,[2] and on Phebus.[3] We are undertaking a program to develop neutron imaging as a diagnostic for capsule performance on the National Ignition Facility (NIF), by first fielding an instrument on the Omega laser. Simulations of capsule burns at NIF drive conditions indicate that the neutron producing (reaction) regions can show a variety of shapes which are related to drive conditions and capsule performance. Figure 1 illustrates the changes in image size and shape with drive conditions for high yield NIF capsules in four cases. These simulated neutron images are postprocessed from two-dimensional (2D) Lasnex[4] radiation hydrodynamic simulations integrating the laser-driven hohlraum and capsule using a Monte Carlo neutron transport code by locating a pinhole and a detector at 20 cm and 20 m from the source, respectively. For clarity here the detector resolution was simulated as 1 μm. Figures 1(a) and 1(c) simulate a copper-doped beryllium capsule driven with a peak radiation temperature of 330 eV.[5] Figures 1(b) and 1(d) simulate the L1000 capsule implosions on the laser megajoule.[6] Figure 1(b) shows the L1000 imploded nearly symmetrically in its laser hohlraum and producing its full yield of 5.2×10^{18} neutrons (14.5 MJ). Figure 1(a) shows the Be330 driven with a pole-hot asymmetry which separates the image into two lobes along the hohlraum axis while still producing full yield (6.0×10^{18} neutrons, or 16.9 MJ). Figure 1(c) is the image of a Be330 which failed to ignite, giving only 1.4×10^{17} neutrons (400 kJ) due to an improper laser pulse time history. There is also created a P4 asymmetry. Figure 1(d) shows a failing L1000 capsule (3.2×10^{15} neutrons or 9 kJ) driven with the proper pulse shape, but an asymmetry due to laser beam pointing. It too has a double lobed structure along the hohlraum axis. The goal of neutron imaging is to provide the size and shape of the neutron-emitting region to help diagnose the cause of capsule failures.

The usefulness of the neutron imaging data is strongly related to the spatial resolution that one can achieve. Figure 2 shows a simulated image of a failing capsule for resolutions of 1, 5, and 10 μm. From this one concludes that resolutions of better than 5 μm are needed to begin to resolve structure in such low yield and compact implosions.

As will be described in this report, resolutions of 5 μm or less appear to be achievable. For lower yields (down to $\sim10^{10}$) resolutions of at least 20 μm seem feasible with

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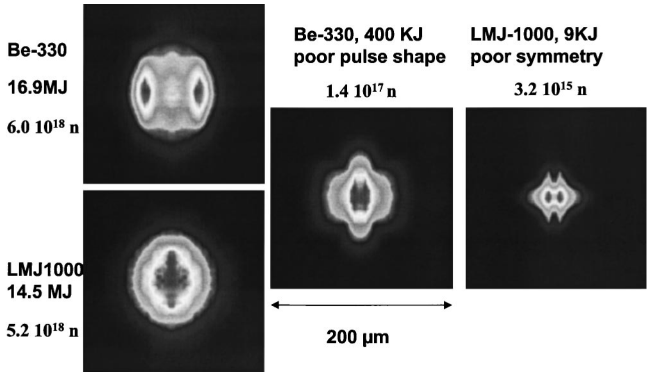

FIG. 1. Simulations show the variety of neutron image sizes and shapes due to asymmetry or improper pulse shaping.

penumbral apertures. We are currently addressing those issues which are crucial to the successful development of these systems using direct-drive capsules at the Omega laser (Laboratory for Laser Energetics, University of Rochester).

II. NIF CONFIGURATIONS

One of the main constraints in the neutron imaging systems considered here is the need for high magnification and a long line of sight. Elements of proposed neutron detectors are at best 300–500 μm diameter. For example to achieve a resolution of 5 μm (two resolution elements) requires a magnification of $\sim$ 200. The location of the detector is then determined by the distance of the neutron imaging assembly (pinhole or penumbral) from the target. Debris and x rays from a target explosion may require a minimum assembly standoff distance of $\sim$10–20 cm. Fortunately, such assemblies are ruggedly built. They are massive, typically made of tungsten, and can tolerate thick aperture covers. A NIF cryogenic target system (which is not yet designed) will probably be compatible with a $\sim$10 cm standoff; the Omega cryogenic system standoff is 5.2 cm. If the center of a pinhole assembly were located 20 cm from the target, then the detector would be located 24–40 m from the source along a very long line-of-sight (LOS).

There are two LOS at NIF which are appropriate for neutron imaging in the equatorial plane of cylindrical hohlraums where expected 2D asymmetries could be viewed normal to their axis. The NIF port labeled NCAM-3 has a clear LOS out to 40 m and beyond, but would require a modest building to house the detector system. This port provides the longest line-of-sight for high resolutions. Port P90-45, which is opposite to the NCAM-2 port, is perpendicular to the first cluster horizontal hohlraum axis and its LOS could be extended out to 24 m, just inside the laser bay.

A key property of these ports is that the lines-of-sight extend out beyond the target bay shield wall. This is essential to eliminate backgrounds due to scattered neutrons and/or neutron-induced gamma rays in the target bay. A prospective system would consist of a 4 μm resolution pinhole centered 20 cm from the target. A detector such as that described in Ref. 7 with a measured efficiency of 27%, but consisting of 0.5 mm diameter plastic scintillator elements and located 50 m from the target would allow observation of an image from a failing capsule ($\sim 5\times10^{15}$ neutrons) utilizing about 4×10^{4} interacting neutrons. Based on the small expected size [$\sim$ 40 μm diam, cf. Figs. 1(d) and 2], the image would have roughly 100 resolution elements with an average of 400 detected neutrons per element. The pinhole assembly would be built of tungsten 15–25 cm long with a double taper of about 0.01° half angle and zero diameter at the confluence of the two tapers. Its full field of view would be $\sim$ 70 μm. The details of how such a pinhole would be fabricated are described in more detail in a following section.

Moderate yield NIF experiments could be imaged with 20 μm resolution. Yields of $10^{10}-10^{12}$ neutrons would require penumbral-imaging systems rather than pinhole systems. Such an imaging system could be fielded using the shorter line-of-sight available through Port P90-45. A penumbral imaging system[7] has been used previously on the Phebus laser with 56 μm resolution and a sensitivity limit of 4×10^{8} neutrons. Comparing to the results from Phebus, a penumbral system giving 20 μm resolution might have a 174 μm radius aperture located 12.5 cm from the source and a detector at 19 m. The sensitivity limit would be $\sim 5\times10^{11}$ neutrons. Image intensifiers would be used in either system between the scintillator and camera, both for gain and for time gating to suppress backgrounds.

III. OMEGA EXPERIMENTS

High yield direct-drive targets at the Omega facility provide an opportunity to test neutron pinhole imaging techniques relevant to NIF. This is currently being pursued by a collaboration between LANL and the CEA. Yields from direct drive capsules can be as high as 1.25×10^{14}. Figure 3 illustrates calculated radial profiles for two different yields near 10^{14} from direct drive targets at Omega. The two curves represent different assumptions about the laser drive on the same 1200 μm diameter, 2.5-μm-thick, glass capsule filled with 20 atm of DT gas. The different profiles represent the typical uncertainty we currently have in the size of the neutron emitting region. A schematic diagram of the Omega neutron imaging system is illustrated in Fig. 4. The system shown here has a magnification of about 50. A first step in the development process will be to use a pinhole with a 60 μm effective diameter, centered 16 cm from the capsule. An imaging system (using 1.5 mm square elements) developed by the CEA will be located 8 m from the target and will produce images from about 2×10^{4} detected neutrons per

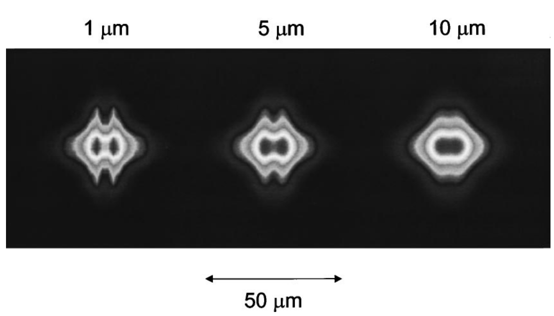

FIG. 2. Image of a failing capsule ($\sim10^{-3}$ full yield) shows asymmetry at 10 μm resolution but higher resolution is informative.

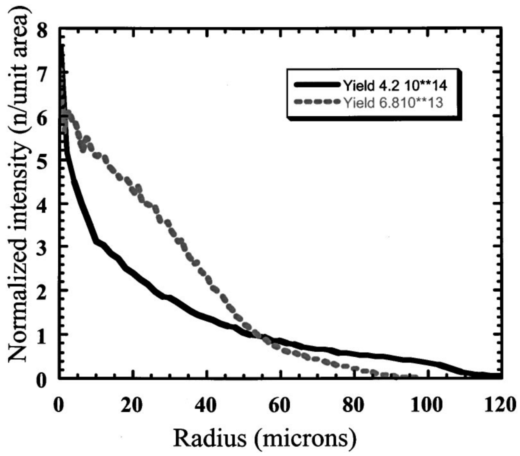

FIG. 3. Calculated neutron image profiles for a 1200 μm diam, 2.5-mm-thick glass microballoon filled with 20 atm. DT driven directly by the Omega laser. The two curves represent the capsule response to different absorbed laser energy.

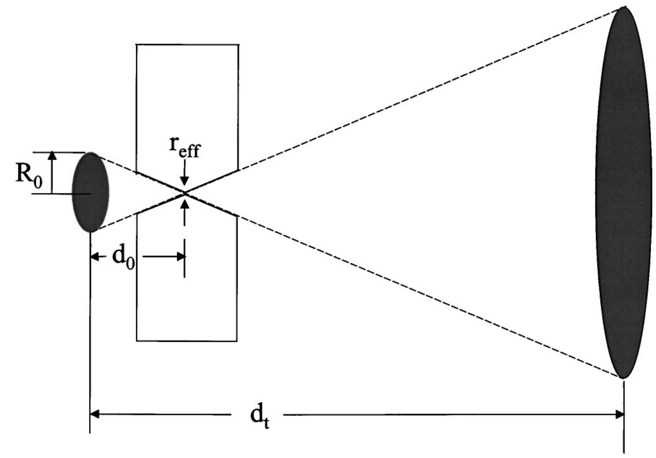

FIG. 5. Conceptual illustration of a pinhole imaging system showing the relation between the key parameters as constrained by the mean free path of neutrons in the pinhole material.

element in the peak. This can then be improved down to about 30 μm resolution using a zero diameter pinhole and smaller (0.5 mm diam) detector elements. The smaller detector has an efficiency of 13% and would produces images from about 10^3 detected neutrons per element in the peak of the image.

Neutron pinholes are less straight forward than optical or x-ray pinholes because of the longer mean free path (mfp) of neutrons in matter. Elements such as gold or tungsten have the shortest mfp, which is of the order of 3 cm at 14 MeV. Figure 5 illustrates the basic constraints placed on pinhole design by the finite mfp for neutrons. The resolution (effective pinhole diameter), image magnification, and field-of-view (FOV) are inter-related, requiring the pinhole design to be a compromise between resolution and FOV which fits within the available geometry and imaging capabilities. The magnification is given by the expression

$$M=(d_t-d_0)/d_0 \sim d_t/d_0,$$

where, as indicated in the figure, d_t is the distance from the source to the detector and d_0 is the distance from the source to the smallest aperture ($\sim$ zero for the higher resolutions) of the pinhole. The effective radius of the pinhole is determined

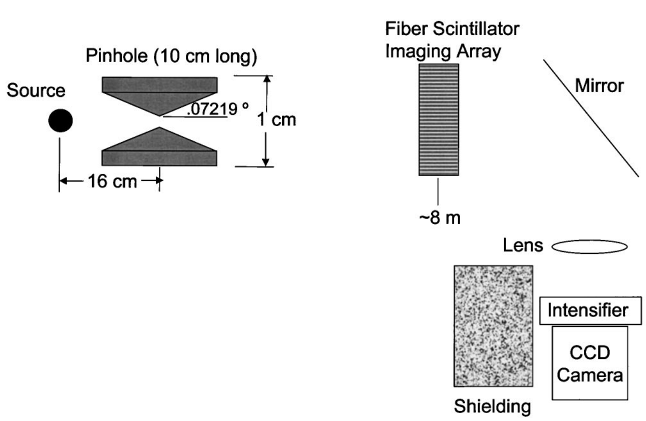

FIG. 4. Schematic diagram of the initial pinhole imaging experiments at Omega giving the primary parameters of the system.

by the neutron transmission through the central region of the pinhole assembly. For a material with a mean free path, λ, and making the assumption that one is dealing with paraxial rays, the effective radius can be expressed as

$$r_{\text{eff}}=\{2r \exp[-t(r)/\lambda]dr\}^{1/2},$$

where $t(r)$ is the path length of pinhole material traversed by a neutron at radius r, and is given by

$$t(r)=2rd_0/R_0,$$

R_0 being the radius of the FOV. One can then derive the relation between magnification, field-of-view, and effective pinhole radius as follows:

$$M=\sqrt{2}r_{\text{eff}}\, d_t/(R_0\lambda).$$

The taper angle of the pinhole assembly decreases as the required resolution increases. Thus, if one requires a given resolution and field-of-view, this fixes the minimum distance from the source to the pinhole, and through the magnification, the distance from the pinhole to the detector. If the detector elements are large enough to contribute significantly to the resolution at this distance, then an even greater magnification may be required.

The fabrication and alignment of such small diameter pinholes requires a significant development effort. Los Alamos has considerable experience in the fabrication of neutron pinholes with diameters as small as 50 μm.[8] The first pinhole to be tested at Omega will be constructed from two halves of tungsten. The inner surface of each half will be plated with gold to use as a working material. A tapered groove will be machined into the gold layer of each half and the two halves will then be mated to produce the completed pinhole assembly. This tapered cut will be started at one end, proceed to the center of the assembly with a programed decrease in depth, then proceed to the other end with a programed increase in depth. This cut can be performed with adequate accuracy using diamond tooling. Since, as shown earlier, the effective radius, and thus resolution of the pinhole is determined by the taper angle of the assembly, a pinhole with an effective radius of 2 μm requires only a different slope of the cutting depth. However, such a pinhole would be located at a larger distance from the source to achieve a particular FOV and this would in turn require a larger distance to the detector. The Omega assembly will have a rectangular cross section 1 cm on a side and a length of 10 cm. The rear surface of the assembly will be faced off accurately perpendicular to the pinhole axis and finished to make an optical reflector of high quality with a gold flashing.

Alignment is clearly one the most difficult aspects of neutron imaging and is currently the main focus of our efforts in developing this technique. Bench tests have been performed to study alignment techniques. The pinhole assembly will be mounted on a remotely controlled stage providing transverse (x, y) positioning and tilt with 30 nm resolution.[9] Thus, the initial alignment need only be sufficiently accurate to insure that the source is within the field-of-view. One can then adjust the pinhole position and pointing to center the source. Reference to Figs. 4 and 5 allows one to conclude that for the Omega system, the field-of-view at the source location is about 200 μm in radius and the half-angle of the pinhole taper is about 1.25 mrad. Thus, for the case where the pinhole axis is accurately parallel to the LOS, a transverse positioning error of 200 μm would still permit the source to be in the edge of the FOV. Likewise for the case where the pinhole is accurately on axis, a pointing error of 1.25 mrad would also permit the source to be seen. Obviously, the actual error would be some combination of these two effects, but if each one separately can be kept sufficiently small relative to its maximum allowance, the initial alignment will be adequate. A mounting tube with internal adjustments for holding the pinhole and an adjustable mirror on its rear end will be mounted on the positioning stage in a ''V'' block with a centering pin. This assembly can be replaced by a pointer assembly having a 2 mm diam ball on its tip and an adjustable mirror on the rear end.

Tests on the bench have been encouraging. Two alignment telescopes, one with autocollimation capability, were mounted on an optical bench and accurately adjusted to point at each other on the same axis. These telescopes then viewed both ends of either the pointer or the pinhole assembly, mounted in the V block on the positioner stage. Without the mirror, the pointer was accurately aligned on both ends to the alignment axis using the positioner stage. The pointer was then replaced by the pinhole holder and the internal adjustments were used to put both ends of the pinhole accurately on the axis (to within 20 μm). The mirrors were then mounted to the assemblies and adjusted to be perpendicular to the axis using the autocollimator. Tests making several exchanges between the pinhole assembly and the pointer indicated that the assemblies reproduced their front (target side) positions to within 20 μm and their pointing to within 25 μrad.

At Omega we intend to pursue a modification of the technique developed for the CEA penumbral system, which will be fielded first in the same location. An autocollimating transit mounted perpendicular to the LOS will be accurately sighted onto the axis between the target chamber center (TCC) and the imaging scintillator using an alignment ball at TCC and right angle mirrors. The positioner assembly with the pointer will then be mounted in a ten inch manipulator (TIM) and inserted to nominal TCC. Using the positioner, the ball tip of the pointer will then be aligned to TCC using the target viewing system. Its pointing will be simultaneously adjusted to be parallel to the LOS using the autocollimator. We estimate this can be done to about 20 μm accuracy in position and less than 20 μrad in pointing. The TIM will then be retracted, the pointer replaced by the pinhole holder, and the TIM reinserted. The TIM has been demonstrated to reproduce its positioning to within about 20 μm. At this point the pinhole should be aligned with sufficient accuracy to obtain an image of the source which can be used to further refine its alignment. Pinholes with smaller fields-of-view can be aligned using an iterative procedure starting with the pointer and progressing from pinholes with larger to smaller fields-of-view.

Initial experiments will be conducted with a penumbral system in June of 2000 and with a pinhole system in September of 2000. Neutron yields of about 10^{14} will be employed and detailed comparisons between the images obtained with the two different approaches will be made. This comparison will allow us to evaluate the compatibility of the NIF systems for achieving consistent results over a wide range of yields and spatial resolutions.

It may be possible to push the resolution of a pinhole imaging system at the Omega facility down to 10–15 μm. This would be based on the verification of alignment techniques at the larger resolutions and a better understanding of signal to background ratios (relative to calculated estimates). A possible way to improve resolution by increasing the detector distance and thus magnification (for a given effective pinhole diameter and FOV size) would be move the imager below floor level. This would also provide a configuration more closely resembling that anticipated at NIF, with a corresponding suppression of backgrounds.

For future work, an improved imaging detector under development at the CEA and consisting of 0.5 mm elements of deuterated scintillator will significantly decrease the contribution of the detector to the overall system resolution. Los Alamos will also explore the fabrication of imaging slits rather than pinholes in order to achieve even higher resolutions in one dimension while maintaining usable signal levels.

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